James Clerk Maxwell

In the same year that Einstein was born, the man who was perhaps his greatest immediate predecessor died. Generally regarded as an abstract theoretician, Maxwell relied heavily on mechanical models

by James R. Newman

James Clerk Maxwell, the greatest theoretical physicist of the 19th century, opened a new epoch of science, and much of what distinguishes our world from his is due to his work. Because his most spectacular discoveries were the fruits of theoretical rather than experimental researches, he is often cited as an outstanding example of a scientist who built his systems entirely with pencil and paper. This notion is false. Maxwell combined a profound physical intuition with a formidable mathematical capacity to gain insights into physical phenomena, never losing sight of the observations to be explained. This blending of the concrete and the abstract was the chief characteristic of almost all his researches.

ENGRAVING OF MAXWELL appears in *The Collected Papers of James Clerk Maxwell.* This illustration and those appearing on the next three pages are from the Burndy Library.

Maxwell was born in Edinburgh on November 13 in 1831, the same year Michael Faraday announced his famous discovery of electromagnetic induction. Descended of an old Scots family whose members were distinguished no less for their individuality, "verging on eccentricity," than for their talents (they included eminent judges, politicians, mining speculators, merchants, poets, musicians), he was the only son of a member of the Scottish bar who took little interest in the grubby pursuits of an advocate but instead managed his small estates, took part in county affairs and gave loving attention to the education of his son. Maxwell's father was a warm and rather simple man with a nice sense of humor and a practical interest in mechanical contrivances. His mother is described as having a "sanguine, active temperament."

Jamesie, as the boy was called, passed his early childhood on the family estate at Glenlair, two days' carriage ride from Edinburgh. He was a nearsighted, lively, affectionate little boy, as persistently inquisitive as his father and as fascinated by machines. To discover of anything "how it doos" was his constant aim. "What's the go of that?" he would ask, and if the answer did not satisfy him, he would add, "But what's the *particular* go of that?" His own first creation was a set of figures for a "wheel of life," a scientific toy which produced the illusion of continuous movement; he was fond of making things with his hands, and in later life knew how to design models embodying the most complex motions and other physical processes.

When Maxwell was nine, his mother died of cancer, the disease that was to

kill him 40 years later. Her death brought the father and son even more closely together. The boy began his schooling a year later as a day student at the Edinburgh Academy. His early school experiences were painful. The master, a dryish Scotsman whose reputation as a pedagogue derived from a book he had written on the irregular Greek verbs, expected his students to be orderly, well-grounded in the usual subjects and unoriginal. Maxwell was deficient in all these departments. He created something of a sensation because of his clothes, which had been designed by his strong-minded father and included such items as "hygienic" square-toed shoes and a lace-frilled tunic. The boys nicknamed him "Dafty" and mussed him up, but he was a stubborn child and in time won the respect of his classmates even if he continued to puzzle them.

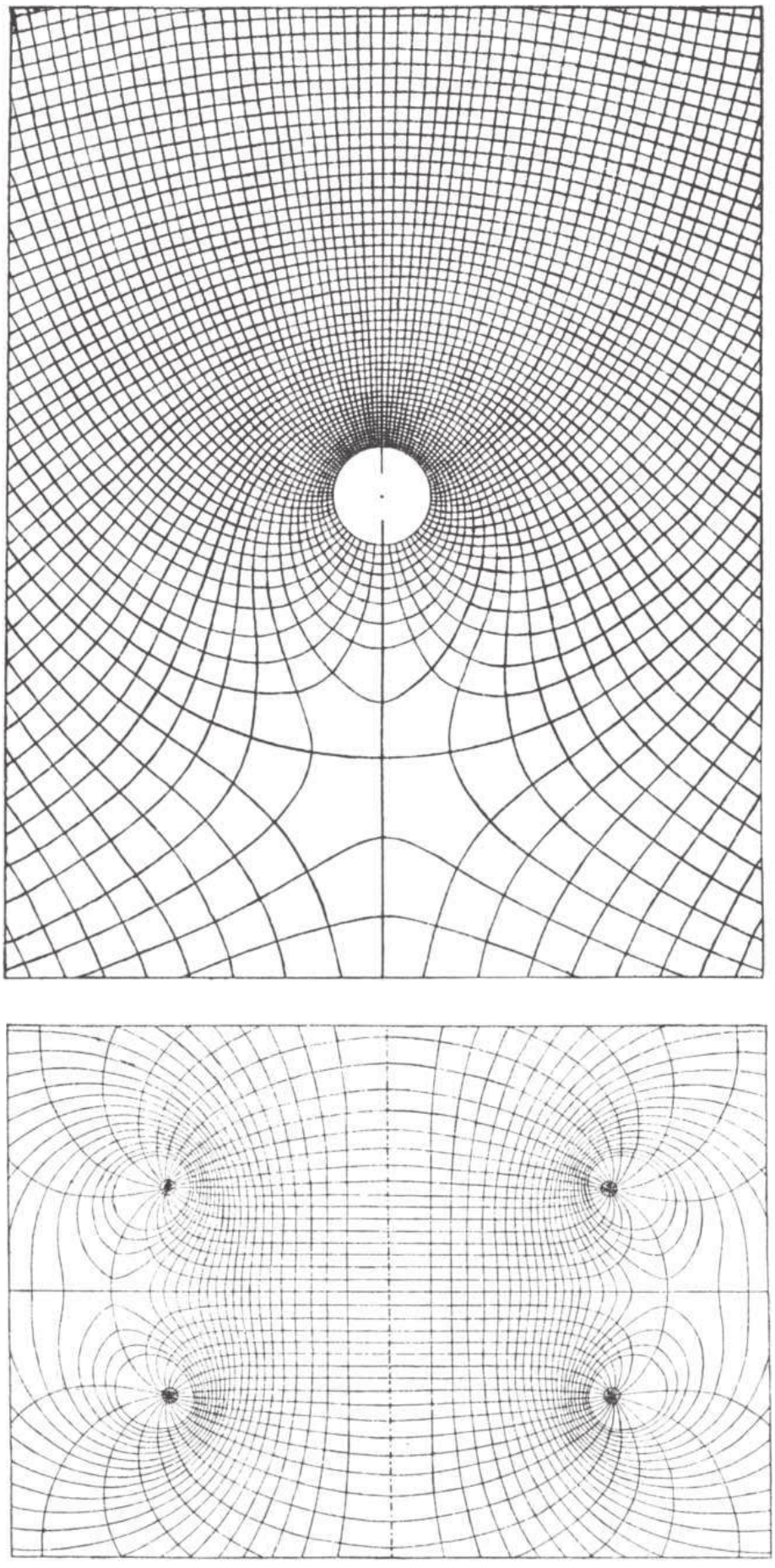
Mathematical Years

At school Maxwell experienced a gradual awakening of mathematical interests. He wrote his father that he had made a "tetra hedron, a dodeca hedron, and two more hedrons that I don't know the wright names for." In his 14th year he won the Academy's mathematical medal and wrote a paper on a method for constructing perfect oval curves with pins and thread. Another prodigious little boy, René Descartes, had anticipated him in this field, but Maxwell's contributions were original. It was a wonderful day for father and son when they heard the boy's paper on ovals read before the Royal Society of Edinburgh by Professor James Forbes. "Met," the father wrote of the event in his diary, "with very great attention and approbation generally."

After six years at the Academy Maxwell entered the University of Edinburgh. He was 16, a restless, enigmatic, brilliantly talented adolescent who wrote not very good but strangely prophetic verse about the destiny of matter and energy:

When earth and sun are frozen clods,
When all its energy degraded
Matter to aether shall have faded

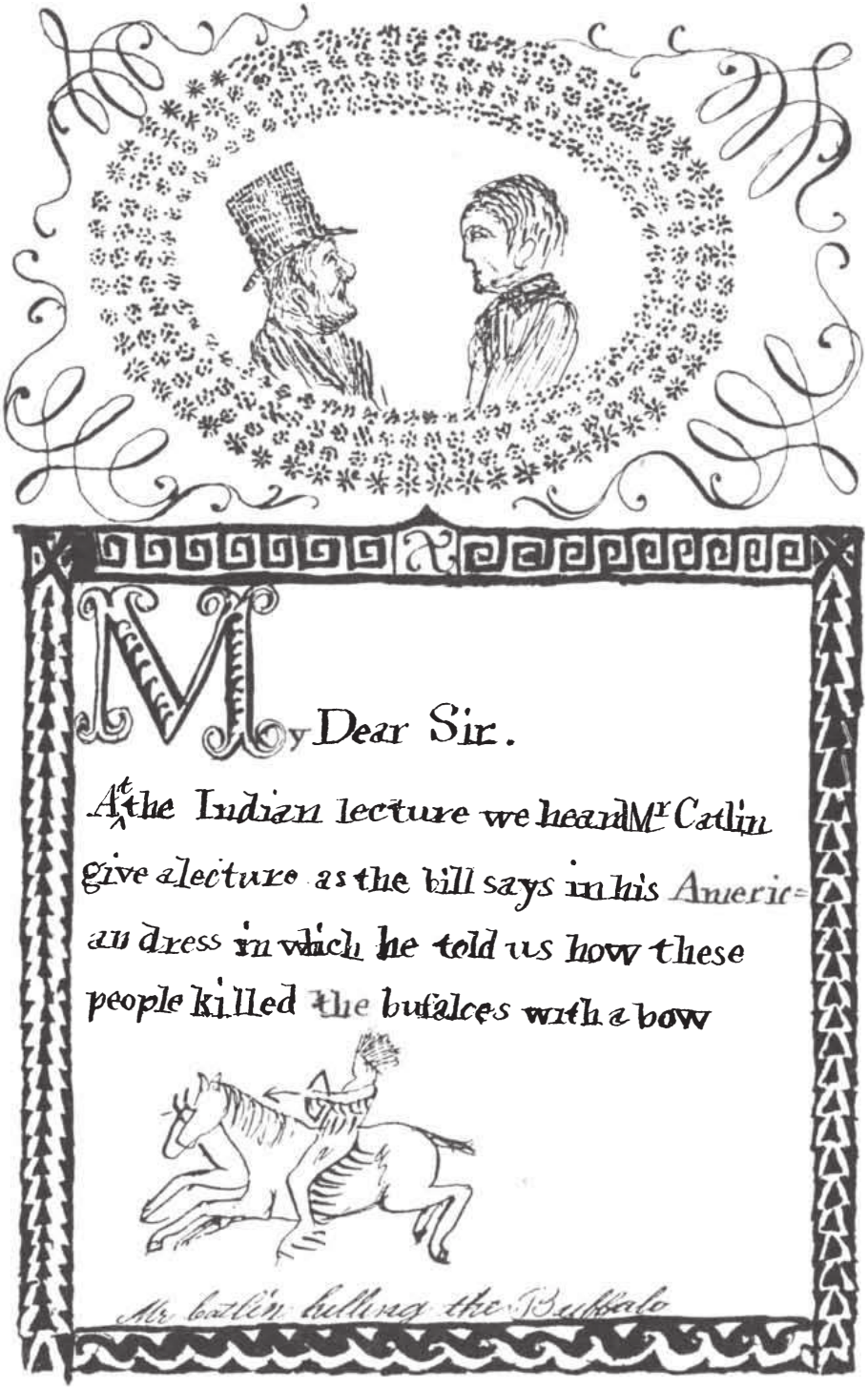
His friend and biographer Lewis Campbell records that he was completely neat in his person, "though with a rooted objection to the vanities of starch and gloves," and that he had a "pious horror of destroying anything—even a scrap of writing paper." He read voraciously and passed much time in mathematical speculations and in chemical,



LINES OF FORCE appear in ***Electricity and Magnetism***. **Top: "Uniform magnetic field disturbed by an electric current in a straight conductor." Bottom: "Two circular currents."**

magnetic and optical experiments. "When at table he often seemed abstracted from what was going on, being absorbed in observing the effects of refracted light in the finger glasses, or in trying some experiment with his eyes—seeing around a corner, making invisible stereoscopes, and the like. Miss Cay [his aunt] used to call his attention by crying, 'Jamesie, you're in a prop [an abbreviation for mathematical proposition].' "

While at Edinburgh, Maxwell regularly attended meetings of the Royal Society, and two of his papers, "On the Theory of Rolling Curves" and "On the Equilibrium of Elastic Solids," were published in the *Transactions*. The papers were read before the Society by others, "for it was not thought proper for a boy in a round jacket to mount the rostrum there." During vacations at Glenlair he wrote long letters reporting his multifarious doings to friends. Many of his letters exhibit an intense interest in moral philosophy, reflecting his social sympathy, his Christian earnestness, the not uncommon 19th-century mixture of rationalism and simple faith. It was a period when men still believed that questions of wisdom, happiness and virtue could be studied as one studies optics and mechanics.

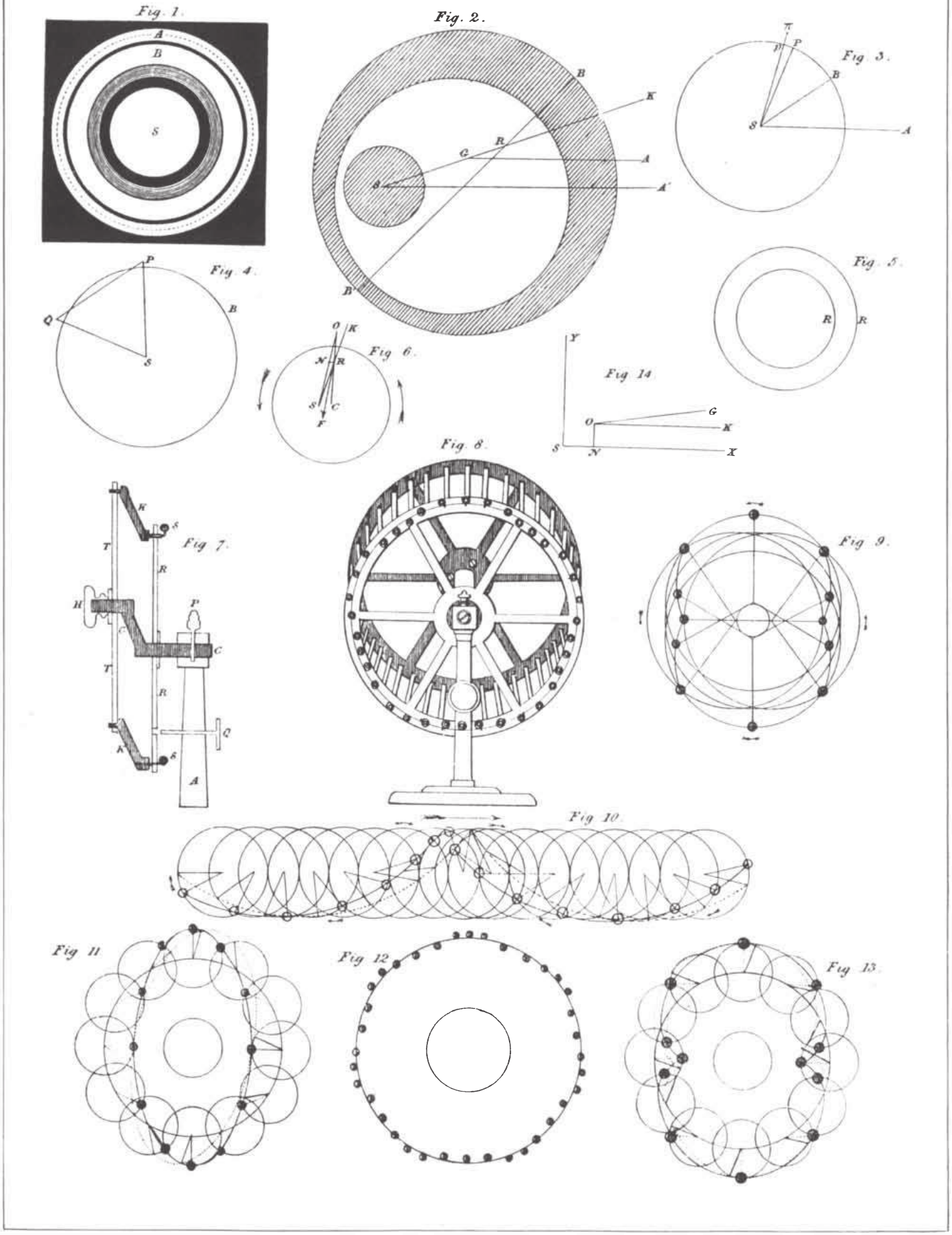

My Dear Sir.
At the Indian lecture we heard Mr Catlin
give a lecture as the bill says in his Americ=
an dress in which he told us how these
people killed the bufalces with a bow
Mr. Catlin hulling the Buffalo

ILLUMINATED LETTER was written by Maxwell to his father in 1843, when the younger Maxwell was 11. The letter refers to a lecture by the American frontier artist George Catlin.

In 1850 Maxwell went on to the University of Cambridge. There he became a private pupil of William Hopkins, considered the ablest mathematics coach of his time, who prepared him for the mathematical tripos, the stiff competitive examinations in which the brightest students competed. Hopkins at once recognized the talents of the black-haired young Scotsman, describing him as "the most extraordinary man I have ever met," and adding that "it appears impossible for [him] to think incorrectly on physical subjects." Besides working hard on his studies, Maxwell joined fully in social and intellectual activities at the University. He was elected to the Apostles, a club of 12 members which for many years included the outstanding young men at Cambridge. A contemporary described Maxwell as "the most genial and amusing of companions, the propounder of many a strange theory, the composer of many a poetic *jeu d'esprit*." Not the least strange of his theories related to economy of sleep. He would sleep from 5 in the afternoon to 9:30, read very hard from 10 to 2, exercise by running along the corridors and up and down stairs from 2 to 2:30 a.m. and sleep again from 2:30 to 7. The dormitory inhabitants were not pleased, but Maxwell persisted in his bizarre experiments. Another of his investigations was a study of the process by which a cat always lands on her feet. He demonstrated that a cat could right herself even when dropped upside down on a table or bed from a height of about two inches.

In the summer of 1853 a "sort of brain fever" seized Maxwell. For weeks he was totally disabled, and he felt the effects of his illness long afterward. This episode was undoubtedly an emotional crisis, but its causes remain obscure. All that is known is that his illness strengthened Maxwell's religious conviction—a deep, earnest piety, leaning to Scottish Calvinism yet never completely identified with any particular system or sect. "I have no nose for heresy," he used to say.

In January, 1854, Maxwell took the tripos in the Cambridge Senate House, with a rug wrapped around his feet and legs (as his father had advised) to mitigate the perishing cold. His head was



MECHANICAL MODEL is depicted in Figure 7 and Figure 8 of this page from Maxwell's essay "On the Stability of the motion of Saturn's Rings." In this essay Maxwell demonstrated that the rings were neither liquid nor solid but were composed of particles.

warm enough. He finished second wrangler behind the noted mathematician Edward Routh. (In another competition at Cambridge, for "Smith's prize," where the subjects were more advanced, Maxwell and Routh tied for first.)

Questions and Answers

After getting his degree Maxwell stayed on for two years at Trinity, studying, lecturing, taking private pupils and doing some experiments in optics. He designed a top with colored paper disks to study the mixing of colors, and he was able to show that suitable combinations of three primary colors—red, green and blue—produced "to a very near degree of approximation" almost every color of the spectrum. For this work in color sensation he later won the Rumford medal of the Royal Society.

Maxwell's most significant activity during the two postgraduate years at Trinity, however, was his reading of Faraday's *Experimental Researches* and entrance upon the studies of electricity which were to lead to his greatest discoveries. Before he left Trinity, he published his first major contribution, the beautiful paper "On Faraday's Lines of Force." In 1856 Maxwell was appointed to the chair of natural philosophy at Marischal College in Aberdeen; he had applied for the post partly to be near his father, whose health had been failing, but his father died a few days before he obtained the appointment. It was an irreparable personal loss to Maxwell; they had been as close as father and son could be. At Aberdeen Maxwell continued his work on electricity. His teaching load was rather light. Although he took teaching seriously, it cannot be said that Maxwell was a great teacher. With classes that were "not bright" he found it difficult to hit a suitable pace. He was unable to heed himself the advice he once gave a friend whose duty it was to preach to a country congregation: "Why don't you give it them thinner?"

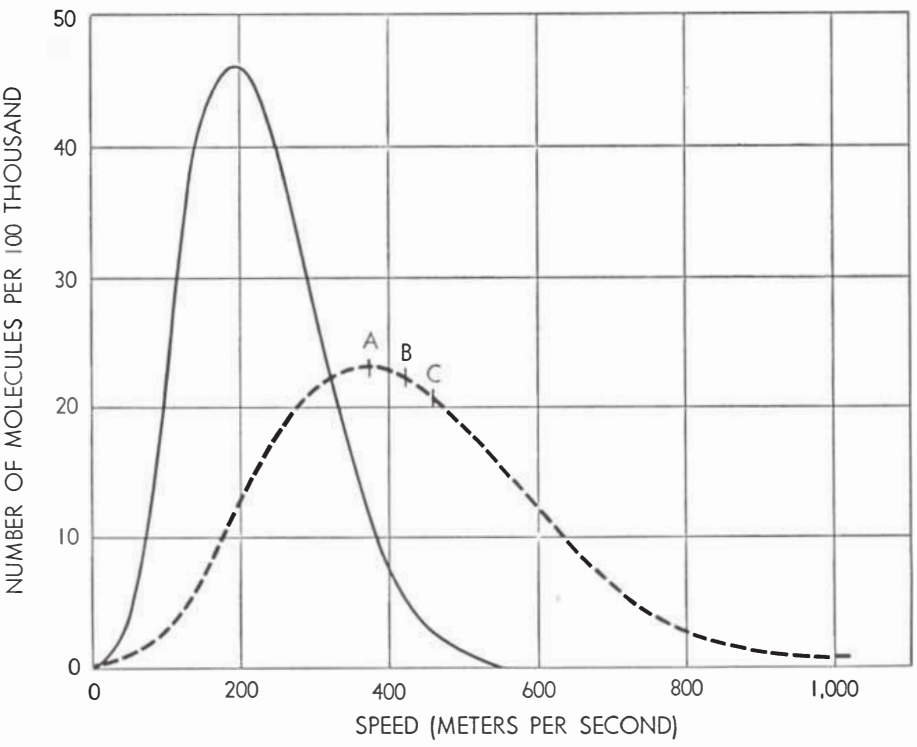
Maxwell's electrical studies at Aberdeen were interrupted by a task which engrossed him for almost two years. He entered a competition for a University of Cambridge prize on the subject of Saturn's rings. Were the rings solid? Were they fluid? Did they consist of masses of matter "not mutually coherent?" The problem was to demonstrate which type of structure adequately explained the motion and permanence of the rings. In a brilliant 68-page essay which Sir George Airy, the Astronomer Royal, described as one of the most remarkable applications of mathematics he had ever seen, Maxwell demonstrated that the only stable structure would be one composed of disconnected particles. His essay won the prize and established him as a leader among mathematical physicists.

His research on Saturn excited his interest in the kinetic theory of gases. Maxwell's predecessors in this field—Rudolf Clausius, Daniel Bernoulli, James Joule and others—had been successful in explaining many of the properties of gases, such as pressure, temperature and density, on the hypothesis that a gas is composed of swiftly moving particles. However, in order to simplify the mathematical analysis they had assumed that all the particles of a gas move at the same speed. Maxwell realized that this was an altogether implausible assumption, for collisions among the molecules must give them various velocities. If the science of gases was to be developed on "strict mechanical principles," it was necessary, he said, to incorporate this fact into the mathematical formulation of the laws of motion of the particles.

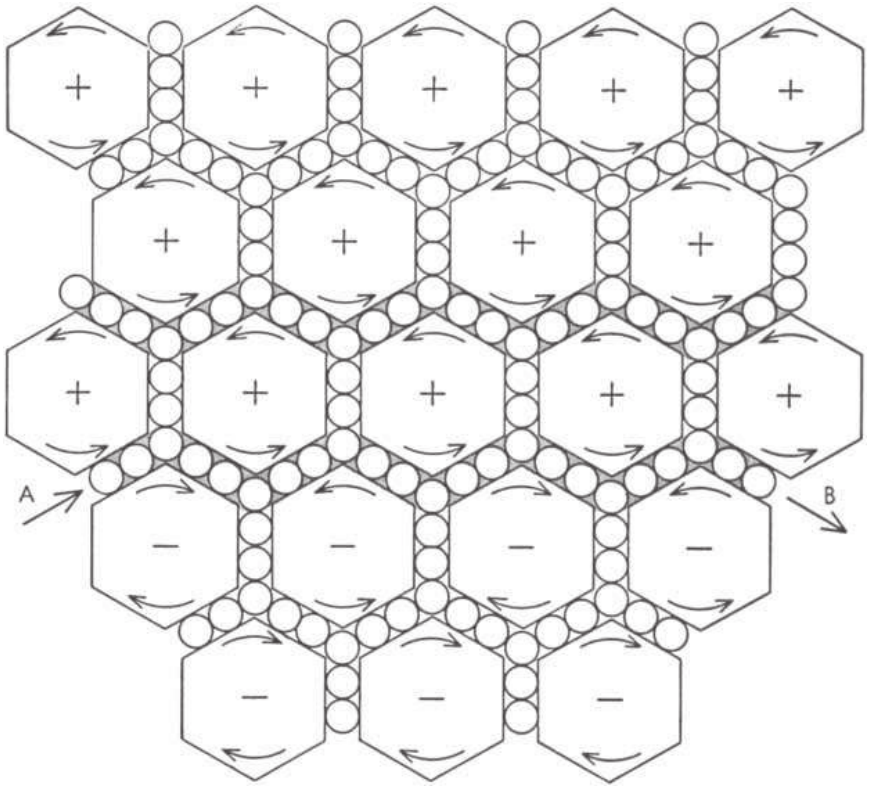
Maxwell's Law of Gases

Maxwell proceeded to examine mathematically the behavior of an assemblage of colliding particles as if they were "small, hard and perfectly elastic spheres acting on one another only during impact." Since the many molecules could not be treated individually, he introduced the statistical method for dealing with them. He supposed that the distribution of velocities among the molecules in a gas would follow the famous bell-shaped frequency curve, which applies to so many phenomena, from the pattern of shots on a target to groupings of men according to height. Thus while the velocity of an individual molecule might elude description, the velocity of a crowd of molecules would not. Having arrived at a quantitative description of the speeds of molecules composing a gas, Maxwell was able to write a precise formula for gas pressure. Curiously enough this expression did not differ from that based on the assumption that the velocity of all the molecules was the same, but at last the right conclusion had been won by correct reasoning. Moreover the generality and elegance of Maxwell's mathematical methods led to the extension of their use into almost every branch of physics.

Maxwell went on to consider another factor which needed to be determined for precise formulation of the laws of gases: namely, the distance a molecule travels, on the average, between colli-



MAXWELL DISTRIBUTION is plotted for the molecules in a gas at 200 degrees centigrade (*solid curve*) and at 0 degrees centigrade (*broken curve*). Each point on the curves indicates the number of molecules in the gas moving at that speed. The speed corresponding to Point A is the most probable velocity of the molecules. The speed corresponding to Point B is the average velocity. The speed corresponding to Point C is the root mean square velocity.



MODEL OF AN ELECTROMAGNETIC FIELD used by Maxwell visualized "molecular vortices" rotating in space. In this illustration the vortices are slender cylinders seen from the end. (Maxwell gave the cylinders a hexagonal cross section to simplify the geometry of the model.) Between the vortices are small "idle wheels." If a row of the idle wheels is moved from A toward B, they cause the adjacent vortices to rotate in opposite directions.

sions—*i.e.*, its mean free path. He reasoned that the mean free path of molecules in a given gas could be measured by the viscosity of that gas. Assume that a gas is composed of groups of molecules with different velocities which slide over one another, thus creating friction. This would account for the viscosity of gases. Now the mean free path of molecules would be related to viscosity in the following way. Imagine two layers of molecules sliding past each other. If a molecule passing from one layer to the other travels only a short distance before colliding with another molecule, the two particles do not exchange much momentum, because near the boundary the difference of velocity between the two layers is small. But if the molecule penetrates deep into the other layer before a collision, the velocity differential will be greater; hence the exchange of momentum between the colliding particles is greater. This amounts to saying that in any gas with high viscosity the molecules must have a long mean free path. Maxwell deduced further the paradoxical fact that the viscosity of a gas is independent of its density, for the increased probability of collisions in a dense gas is offset by the fact that in such a gas a molecule will not travel far into a different layer before colliding. On balance, then, the momentum conveyed across each unit area per second remains the same regardless of density.

Thus Maxwell constructed a mechanical model of a gas as an assemblage of crowds of particles "carrying with them their momenta and their energy," traveling certain distances, colliding, changing their motion, resuming their travels, and so on. His picture made it possible to account in precise quantitative terms for a gas's various properties—viscosity, diffusion, heat conduction. Altogether it was a scientific achievement of the first rank. The model has since been criticized, on the grounds, for example, that molecules are not hard nor perfectly elastic, like billiard balls, nor is their interaction confined to the actual moment of impact. Yet despite the inadequacies of the model and errors of reasoning, the results, which, as Sir James Jeans said, "ought to have been hopelessly wrong," turned out to be exactly right, and Maxwell's law for the behavior of gases is in use to this day.

The German physicist Ludwig Boltzmann, who recognized at once the significance of these discoveries, set to work refining and generalizing Maxwell's

the story of

Magnetic Domains

If your responsibilities include research, development and design work involving magnetic materials, you'll be interested in the recently published article, "Magnetic Domains," by Dr. Klaus J. Sixtus of the Indiana Steel Products Co.

Dr. Sixtus, well-known authority in the field of magnetics research, tells (1) what magnetic domains are, (2) what size they have, (3) what determines this size, and (4) how this knowledge has helped in the development of new types of permanent magnet materials.

"Magnetic Domains" appeared in the November-December, 1954 issue of *Applied Magnetics*, a bi-monthly publication carrying practical information about permanent magnets and their application to industrial and consumer products.

If you would like a copy of this issue, please send your request to Department J-6.

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proof. He showed that the Maxwell distribution of velocities was the only possible equilibrium state of a gas. This equilibrium state, as both men realized, is the thermodynamic condition of maximum entropy—the most disordered state, in which the least amount of energy is available for useful work.

The concept of entropy led Maxwell to one of the celebrated images of modern science, namely that of the sorting demon. Increasing entropy is man's fate because we are not very bright. But a demon more favorably endowed could sort out the slow- and fast-moving particles of a gas, thereby changing disorder into order and converting unavailable into available energy. Maxwell imagined one of these small, sharp fellows "in charge of a frictionless, sliding door in a wall separating two compartments of a vessel filled with gas. When a fast-moving molecule moves from left to right, the demon opens the door; when a slow-moving molecule approaches, he (or she) closes the door. The fast-moving molecules accumulate in the right-hand compartment, and slow ones in the left. The gas in the first compartment grows hot and that in the second cold." Thus the demon would thwart the second law of thermodynamics. Living organisms, it has been suggested, achieve an analogous process; as Erwin Schrödinger has phrased it, they suck negative entropy from the environment in the food they eat and the air they breathe.

Maxwell and Boltzmann, working independently and in a friendly rivalry, at first made notable progress in explaining the behavior of gases by statistical mechanics. After a time, however, formidable difficulties arose. For example, they were unable to write accurate theoretical formulas for the specific heats of certain gases (the quantity of heat required to raise the temperature of a body of the gas by a given amount). Explanation of the discrepancies they found had to await the development of quantum theory, which showed that the spin and vibration of molecules were restricted to certain values. But neither quantum theory nor relativity, nor the other modes of thought constituting the 20th-century revolution in physics, would have been possible had it not been for the brilliant labors of these natural philosophers in applying statistical methods to the study of gases.

Marriage

In February, 1858, Maxwell wrote his aunt, Miss Cay: "This comes to tell you that I am going to have a wife." "Don't be afraid," he added, "she is not mathematical, but there are other things besides that, and she certainly won't stop mathematics." His bride was Katherine Mary Dewar, daughter of the Principal of Marischal College. Their union became very close: they enjoyed doing things together—horseback riding, reading aloud to each other, traveling—and he even found useful tasks for her in his experimental work. The marriage was childless, but this very fact increased the couple's dependency and devotion.

In the summer of 1860 Maxwell moved to London as professor of natural philosophy at King's College. He remained there for five years. Living in London offered him the opportunity to see something of Faraday, with whom, up to this time, Maxwell had had only correspondence, and to make the acquaintance of other scientists. He was no solitary. "Work is good, and reading is good, but friends are better," he wrote to his friend Litchfield. Despite social distractions and arduous teaching duties at King's, the five years in London were the most productive of Maxwell's life. He continued his work on gases. In the large garret of his house in Kensington he measured the viscosity of gases and obtained practical confirmation of his theoretical work. (To maintain the necessary temperature a fire had to be kept up in the midst of very hot weather and kettles kept boiling to produce steam which would be allowed to flow into the room. Mrs. Maxwell acted as stoker.) But his major work was in the theory of electricity, from which he had been diverted and to which he now returned.

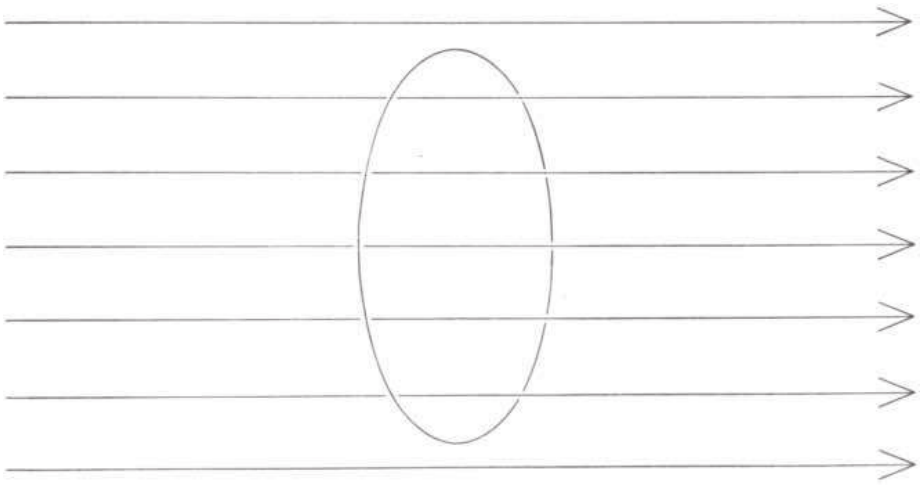
A Model for Electricity

Faraday's experiments had crowned a century of researches (by Coulomb, Oersted, Ampère and others) which had established many facts about the behavior of electricity and its link with magnetism. They had shown that electric charges attracted and repelled each other according to a law like that of gravitation (in proportion to the product of the charges and in inverse proportion to the square of the distance between the charges); that a current produces a magnetic field, and a moving magnet produces a current; that an electric current in one circuit can induce a current in another.

What absorbed Maxwell was the attempt to explain these phenomena. What was a field? How did electricity and magnetism exert their influence through space? Faraday had suggested a new concept to answer these questions, and it was his idea that excited Maxwell's interest.

Most theorists had pursued the analogy of electricity to gravitation and had sought to explain the phenomena in terms of "action at a distance." They imagined a charge (or mass) situated at one point in space mysteriously influencing a charge (or mass) at another point, with no linkage or connection of any kind between the charges (or masses). Faraday proposed to explain electricity as a mechanical system. He asserted that the instrumentality of electric and magnetic action was lines of force running through space—not merely imaginary lines but actual, physical entities, with properties of tension, attraction, repulsion, motion and so on.

Maxwell admirably summarized the cleavage between the two views: "Faraday, in his mind's eye, saw lines of force traversing all space, where the mathema-



CURL of Maxwell's equations is suggested by this diagram. The arrows are a moving magnetic field. The circle is the electric field which "curls" around the magnetic lines of force.

ticians saw centres of force attracting at a distance; Faraday saw a medium where they saw nothing but distance; Faraday sought the seat of the phenomena in real actions going on in the medium, they were satisfied that they had found it in a power of action at a distance impressed on the electric fluids."

Maxwell believed in Faraday's concept, and he set out to develop it. In his first paper, "On Faraday's Lines of Force," he tried to imagine a physical model, embodying Faraday's lines, whose behavior could be reduced to formulas and numbers. He did not suggest that the model represented the actual state of things, but he felt that it was important "to lay hold of a clear physical conception, without being committed to any theory founded on the physical science from which that conception is borrowed." Such a method would protect the investigator against being led into a blind alley of abstractions or being "carried beyond the truth by a favorite hypothesis."

Maxwell proposed a hydrodynamic model, in which he incorporated Faraday's lines of force in the form of "tubes of flow" carrying an incompressible fluid such as water. The fluid moving through the tubes represented electricity in motion; the form and diameter of the tubes gave information as to the strength and direction of the flow. The velocity of the fluid was the equivalent of electrical force; differences of fluid pressure were analogous to differences of electrical pressure or potential; pressure transmitted from tube to tube by way of the elastic tube surfaces furnished an analogue to electric induction. By applying the established equations of hydrodynamics to such a system, Maxwell was able to account for many of the observed facts concerning electricity.

It was a wonderful paper, and Faraday expressed his appreciation. "I was at first almost frightened," he wrote Maxwell, "when I saw such mathematical force made to bear upon the subject, and then wondered to see that the subject stood it so well." Other students, however, thought the subject stood it not at all well. Electricity was mysterious enough without adding tubes and incompressible fluids. But Maxwell, who had had good training in being considered queer, went on with the task of extending Faraday's ideas.

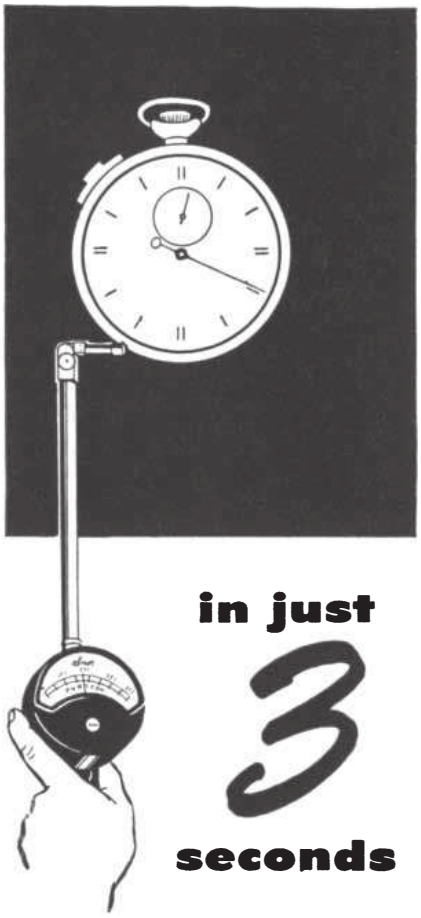
Cylinders and Balls

Maxwell's second great memoir, "On Physical Lines of Force," was published after he returned to the subject of electricity in London. He now constructed a more elaborate model to account not only for electrostatic effects but also for magnetic attraction and electromagnetic induction. In the new model "molecular vortices" rotating in space were the agents that produced magnetic fields. A molecular vortex may be thought of as a slender cylinder which rotates around the lines of magnetic force. The velocity of rotation depends on the intensity of the magnetic force. Two mechanical effects are associated with the cylinders: tension in the direction of the lines of force, and lateral pressure arising from the centrifugal force produced by the rotating cylinders. Combined, these effects mechanically reproduce magnetic phenomena: magnetism is a force exerted both along the axis and outward from the axis.

Maxwell proceeded to show how this curious arrangement might explain the production of a magnetic field by an electric current and of a current by a changing field. He supposed first that a uniform magnetic field consists of a portion of space filled with cylinders rotating at the same velocity and in the same direction "about axes nearly parallel." But immediately a puzzle confronted him. Since the cylinders are in contact, how can they possibly rotate in the same direction? As everyone knows, a rotating wheel or cylinder causes its neighbor to rotate in the opposite direction. Maxwell hit upon a pretty idea. He supposed that rows of small spheres, like layers of ball bearings, lay between the cylinders and acted as gears (in Maxwell's words, "idle wheels"). Thus the cylinders all rotated in the same direction.

And now, as just reward for his ingenuity, Maxwell found that the spheres could be made to serve another even more valuable purpose. Think of them as particles of electricity. Then by purely mechanical reasoning it can be shown that their motions in the machine of which they are a part serve to explain many electrical phenomena.

Consider these examples. In an unchanging magnetic field the cylinders all rotate at the same constant rate. The little rotating spheres keep their position; there is no flow of particles, hence no electric current. Now suppose a change in the magnetic force. This means a change in the velocity of rotation of the cylinders. As each cylinder is speeded up, it transmits the change in velocity to its neighbors. But since a cylinder now rotates at a slightly different speed from its neighbor, the spheres between them are torn from their positions by a kind of shearing action. This



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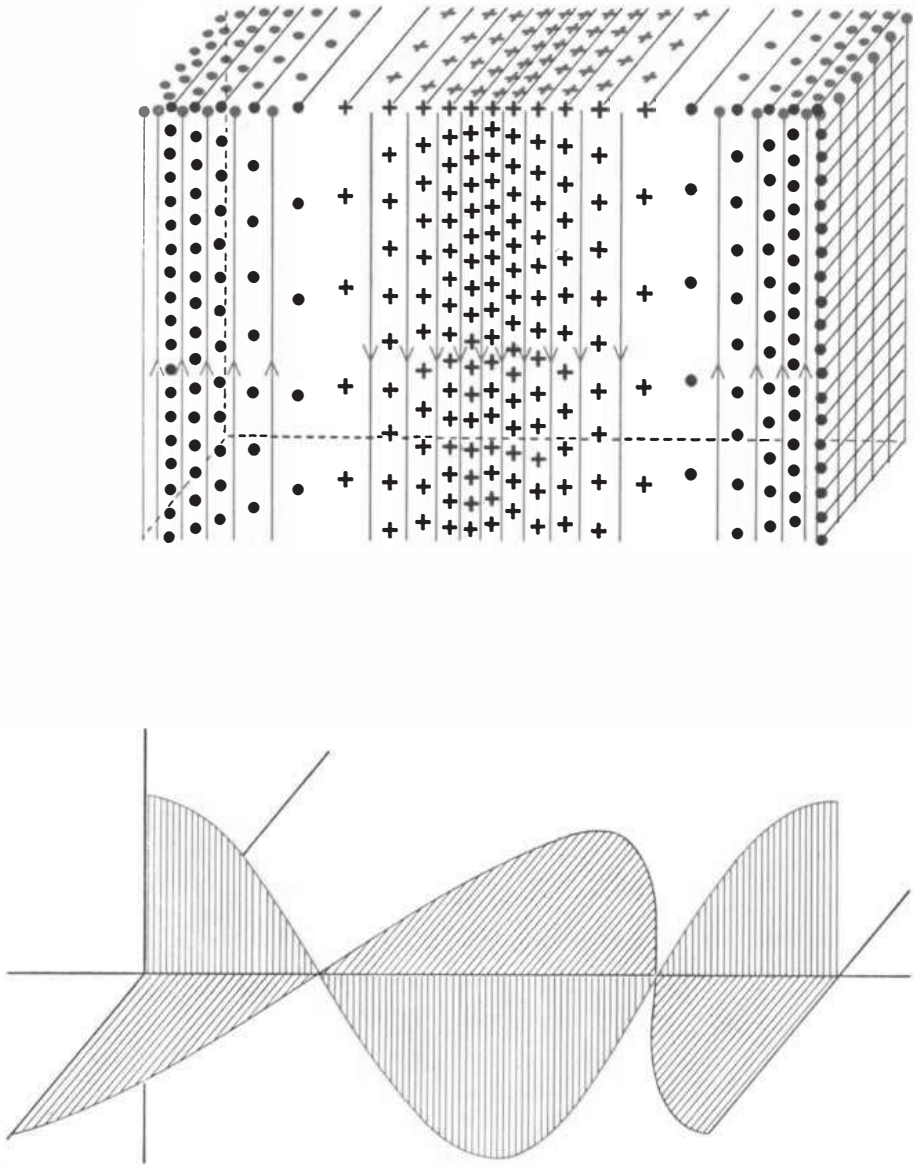

ELECTROMAGNETIC WAVE was visualized by Maxwell as a moving disturbance which tended to separate positive (*plus sign*) and negative (*dot*) charges. In the drawing at the top magnetic lines of force (*arrows*) lie at right angles to the direction in which the disturbance is moving. The drawing at the bottom depicts the two components of the electromagnetic wave. The electrical component is shown in black; the magnetic component, in color.

motion of translation of the particles is an electric current.

Observe now how the model begins to live a life of its own. Though designed primarily to demonstrate how magnetic changes produce electric currents, it also suggested to Maxwell a mechanism whereby a change in electric force might produce magnetism. Assume the spheres and cylinders are at rest. If a force is applied to the spheres of electricity, causing them to move, the cylinders of magnetism with which they are in contact will begin to rotate, thereby producing a magnetic force. Moreover, the model holds up even as to details. Take a single illustration. An examination of Maxwell's model shows that the cylinders will rotate in the direction perpendicular to the motion of the spheres, thus bearing out the observation that a magnetic field acts at right angles to the flow of a current!

"I do not bring it forward," Maxwell wrote of his system, "as a mode of connection existing in Nature. . . . It is, however, a mode of connection which is mechanically conceivable and easily investigated, and it serves to bring out the actual mechanical connections between the known electromagnetic phenomena." Among the other "mechanical connections" Maxwell was able to demonstrate were electrical repulsion between two parallel wires carrying currents in opposite directions (ascribed to the centrifugal pressures of the revolving cylinders on the electrical particles in the model) and the induction of currents (the result of communication of rotary velocity from one cylinder to another).

Maxwell was not done with the model. It had yet to pass the supreme test: that is, to supply a mechanical explanation of the origin of electromagnetic waves. To orient ourselves in this matter we must examine briefly the question of condensers and insulators.

Faraday in his experiments had come upon a curious fact. The type of insulating material used in a condenser made a considerable difference in the condenser's capacity to take or to hold a charge. This was difficult to understand if all insulators were equally impermeable to an electric current. With the help of his model, Maxwell advanced a bold hypothesis. In an insulating material the little electrical particles somehow are unable to move freely from cylinder to cylinder; hence no current can flow. However, it was known that "localized electric phenomena" did occur in insulators. Maxwell suggested that these phenomena were currents of a special kind. When an electric force acts on an insulator, the particles of electricity are "displaced" but not torn loose; that is, they behave like a ship riding at anchor in a storm. They move only a limited distance, to the point where the force pushing them is balanced by the resistance of the elastic cylinders. As soon as the impelling force ceases to act, the particles snap back to their original positions. When a particle snaps back, it overshoots and oscillates about its fixed position. The oscillation is transmitted through the insulator as a wave. Thus for a brief instant a displacement current flows, for the wave is the current. If the electric force applied to the insulator is varied continually, it will produce a continually varying displacement wave: in other words, a continuing current.

Maxwell next arrived at an epochmaking conclusion. It had to do with the relation of the velocity of the displacement wave, or current, to that of light. For the point of departure we must go back to earlier work by the German physicists Wilhelm Weber and Friedrich Kohlrausch on the relationship between electrostatic and electrodynamic forces. The electrostatic unit of charge was defined as the repulsion between two like unit charges at unit distance apart. The electrodynamic unit was defined as the repulsion between two measured lengths of wire carrying currents "which may be specified by the amount of charge which travels past any point in unit time." In order to compare the repulsion between static charges with that between moving charges, a factor of proportionality must be introduced, since the units are different. This factor turns out to be a

velocity, for since the length of the wires is fixed, and the number of units of electricity passing a given point in a given time can be measured, what the investigator must consider is length divided by time, or velocity. Weber and Kohlrausch had found that the velocity of propagation of an electric disturbance along a perfectly conducting wire was close to 3×10^{10} centimeters per second. This was an astonishing coincidence, for the figure was about the same as the velocity of light, determined a few years earlier.

Maxwell pursued the coincidence. He himself confirmed the Weber-Kohlrausch results, using an ingenious torsion balance to compare the repulsion between two static charges and two wires carrying currents, and at about the same time he calculated the velocity of displacement currents in a dielectric (nonconductor). The resulting values tallied closely. In other words, currents in a wire, displacement currents in a dielectric, and light in empty space (which of course is a dielectric) all traveled with the same velocity. With this evidence at hand Maxwell did not hesitate to assert the identity of the two phenomena—electrical disturbances and light. "We can scarcely avoid the inference," he said, "that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena."

Maxwell's Equations

Maxwell now had to outgrow his model. In "A Dynamical Theory of the Electromagnetic Field," published in 1864, he displayed the architecture of his system, as Sir Edmund Whittaker has said, "stripped of the scaffolding by aid of which it had first been erected." The particles and cylinders were gone; in their place were the field and the aether, a special kind of "matter in motion by which the observed electromagnetic phenomena are produced." The matter composing the aether had marvelous properties. It was very fine and capable of permeating bodies; it filled space with an elastic medium. It was the vehicle of "the undulations of light and heat."

For all its refinements and subtleties the aether was no less a mechanical rig than the cylinders and balls. It could move, transmit motions, undergo elastic deformations, store potential (mechanical) energy and release it when the deforming pressures were removed. As a mechanism, Maxwell said, it "must be subject to the general laws of dynamics, and we ought to be able to work out all the consequences of its motion, provided we know the form of the relation between the motions of the parts." Applying himself to this task, he devised the famous Maxwellian equations of the electromagnetic field. In their most finished form they appear in his *Treatise on Electricity and Magnetism*, which presents the results of 20 years of thought and experiment.

Maxwell based the equations on four principles: (1) that an electric force acting on a conductor produces a current proportional to the force; (2) that an electric force acting on a dielectric produces displacement proportional to the force; (3) that a current produces a magnetic field at right angles to the current's lines of flow and proportional to its intensity; (4) that a changing magnetic field produces an electric force proportional to the intensity of the field. The third and fourth principles exhibit a striking symmetry. The third is Faraday's law of electromagnetic induction, according to which "the rate of alteration in the number of lines of magnetic induction passing through a circuit is equal to the work done in taking unit electric charge round the circuit." Maxwell's complementary law, the fourth principle, is that "the rate of alteration in the number of lines of electric force passing through a circuit is equal to the work done in taking a unit magnetic pole round it."

On this foundation two sets of symmetrical equations can be erected. One set expresses the continuous nature of electric and magnetic fields; the second set tells how changes in one field produce changes in the other.

How does the concept of the field enter the theory? We have followed Maxwell as he stripped his model of its particles and cylinders and reduced it to an aethereal medium. Now he robs the medium of almost all its attributes other than form. Its properties are all purely geometric. The grin is left but the cat is gone. It is a perfect example of mathematical abstraction.

The aether is a thing that quivers when it is prodded, but does nothing on its own. An electromagnetic field consists of two kinds of energy: electrostatic, or potential, energy, and electrodynamic, or kinetic, energy. The aether, like a universal condenser, may be conceived as storing energy—in which case, being elastic, it is deformed. Since the aether fills all space and therefore penetrates conductors as well as dielectrics, it no longer makes any difference whether we deal with a conduction current or a displacement current; in either case the

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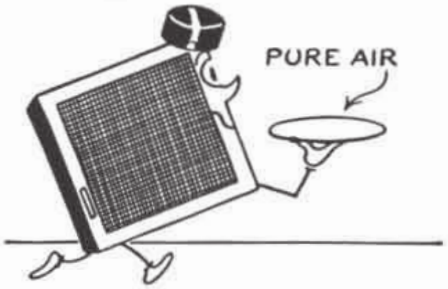

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aether is set in motion. This motion is communicated mechanically from one part of the medium to the next and is apprehended by us as heat, light, mechanical force (as in the repulsion between wires) or other phenomena of magnetism and electricity. The ruling principle of all such phenomena, it should be observed, is that of least action. This is the grand overriding law of the parsimony of nature: every action within a system is executed with the least possible expenditure of energy. It was of the first importance to Maxwell that electrical phenomena should satisfy the principle, for otherwise his mechanical explanation of the phenomena would not have been possible.

Div and Curl

With these points in mind, we may examine a set of Maxwell's equations in a form which describes the behavior of an electromagnetic field in empty space. No conductors or free charges are present; the source of the field is some other region of space.

The first equation then reads:

$$\text{div } E = 0$$

E represents the electric field strength, which varies in time and from place to place. Div is an abbreviation for divergence. It signifies a mathematical operation which gives a rate of change. The equation says that the number of electric lines of force (representing the field strength) which enter any tiny volume of space must equal the number leaving it. That is, the rate of change in the number of lines is zero, and they can neither be created nor destroyed.

The second equation reads:

$$\text{div } H = 0$$

It makes the same assertion for the magnetic field H as the first equation makes for the electric field.

The third equation is:

$$\text{curl } E = -\frac{1}{c}\frac{\partial H}{\partial t}$$

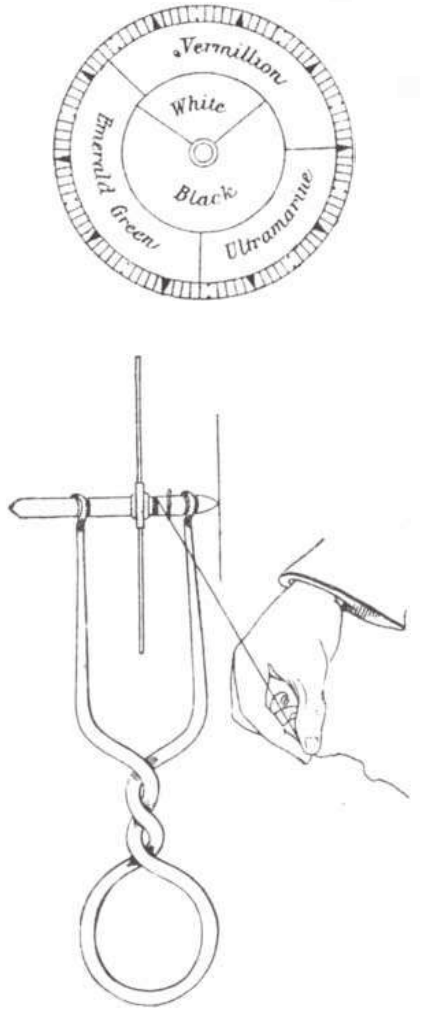
This is Maxwell's statement of Faraday's law of induction: it describes what happens in a changing magnetic field. The expression $\partial H/\partial t$ simply states the rate of change of the magnetic field. The changing magnetic field creates an electric field, and this fact is expressed on the left side of the equation, where the term "curl" signifies a mathematical operation dealing with rotation. The equation is more than analytic; it actually gives a picture of the event. A simple diagram may help make it clear [*see illustration on page 64*]. Suppose the existence of a magnetic field uniform over a region of space. A bundle of parallel lines represents the intensity and direction of this field. If the field is changed (by motion or by increase or reduction of strength), it produces an electric field which acts in a circle around the lines of magnetic force. By summing the work done in moving unit electric charge around the circle we obtain what is called the net electromotive force around the circle. If the circle were made of wire, the changing magnetic lines would of course induce the flow of a current; but even without a wire a force would be induced. Dividing this force by the area enclosed by the circle gives the net electromotive force (per unit area) which "curls" around the circle. Now imagine the circle growing smaller and smaller and shrinking finally to the point P. By this limiting process we obtain a limiting value of the net electromotive force per unit area: this is curl E at P. Thus the equation says that the limiting value of electromotive force per unit area equals the rate of change of H at the point P, multiplied by the tiny negative fraction, $-1/c$. The symbol c here stands for the ratio of the electrostatic to the electromagnetic units of electricity. It is required to translate E (an electrostatic phenomenon) and H (an electrodynamic phenomenon) into the same system of units. The equation explains how Maxwell was able to connect electrical and magnetic phenomena with the velocity of light, for c is in fact that velocity.

The last equation is:

$$\text{curl } H = \frac{1}{c}\frac{\partial E}{\partial t}$$

It says that except for the change of algebraic sign (which has to do with the directions of the fields), the roles of E and H in the preceding equation may be reversed. At any given point and instant the magnetic force per unit of area created by a changing electric field is equal to the time rate of change of the electric field multiplied by the tiny positive fraction $1/c$. Now this rate of change is none other than Maxwell's displacement current. For since the changes are taking place in the dielectric known as empty space, the only currents that can flow are displacement currents. Prior to Maxwell it was thought that a magnetic field could be produced only by currents which flowed in wires. It was Maxwell's great discovery, deduced mechanically from his model and expressed mathematically in this equation, that a time-varying electric field produced a magnetic force even in an insulator or empty space.

According to Maxwell's theory the introduction of a time-varying electric force in a dielectric produces displacement waves with the velocity of light. These periodic waves of electric displacement are accompanied by a periodic magnetic force. The wave front itself comprises electric vibrations at right angles to the direction of propagation, and a magnetic force at right angles to the electric displacement. The compound disturbance is therefore called an electromagnetic wave. A light wave (a displacement wave), as Henri Poincaré later elaborated, is "a series of alternating currents, flowing in a dielectric, in the air, or in interplanetary space, changing their direction 1,000,000,000,000,000 times a second. The enormous inductive effect of these rapid alternations produces other currents in the neighboring



COLOR WHEEL is depicted in Maxwell's essay "Experiments on Colour, as perceived by the Eye, with remarks on Colour-Blindness." The wheel is shown at the top. The apparatus for rotating it is at the bottom.

portions of the dielectric, and thus the light waves are propagated from place to place."

The electromagnetic theory of light was testable experimentally, and stood up remarkably well in laboratory trials. There were also other ways of testing Maxwell's theory. If his reasoning was correct, different sources of disturbance should produce other electrical waves at frequencies different from those of light. They would not be visible; yet it should be possible to detect them with appropriate instruments. Maxwell did not live to see their discovery, but 10 years after his death Heinrich Hertz won the race to demonstrate their existence. In a series of brilliant experiments he succeeded in generating electric radio waves. He concluded that the connection "between light and electricity . . . of which there were hints and suspicions and even predictions in the theory, is now established. . . . Optics is no longer restricted to minute aether waves, a small fraction of a millimetre in length; its domain is extended to waves that are measured in decimetres, metres and kilometres. And in spite of this extension, it appears merely . . . as a small appendage of the great domain of electricity. We see that this latter has become a mighty kingdom."

Construction Work

Maxwell completed his great work on electromagnetic theory while "in retirement" at Glenlair. It drew only part of his energy. As a "by-work" during the same period he wrote a textbook on heat and a number of papers on mathematics, color vision and topics of physics. He maintained a heavy scientific and social correspondence, enlarged his house, studied theology, composed stanzas of execrable verse, rode his horse, went on long walks with his dogs, visited his neighbors and played with their children, and made frequent trips to Cambridge to serve as moderator and examiner in the mathematical tripos.

In 1871 a chair in experimental physics was founded at Cambridge. It is hard to realize that at the time no courses in heat, electricity and magnetism were being taught there, and no laboratory was available for the pursuit of these arcane matters. The University, as a contemporary scholar delicately observed, "had lost touch with the great scientific movements going on outside her walls." A committee of the faculty began to bestir itself, a report was issued, and the lamentable facts fell under the gaze of the Duke of Devonshire,

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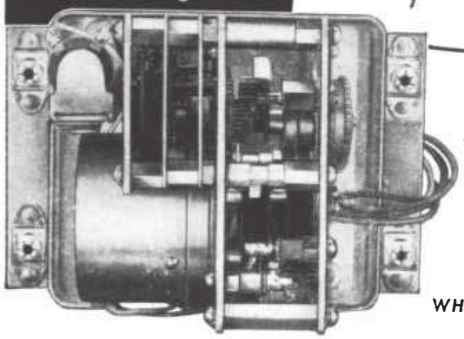

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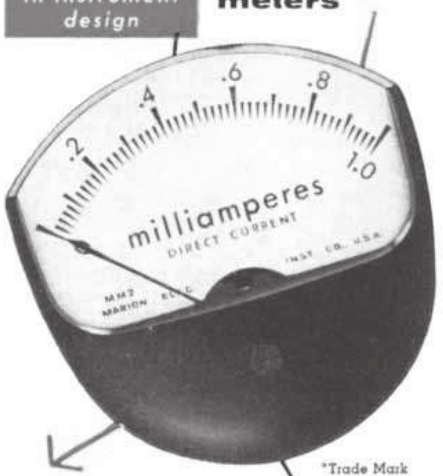

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chancellor of the University. He offered the money for the building and furnishing of the famous Cavendish Laboratory. Maxwell, though at first reluctant to leave Glenlair, yielded to the urging of his friends to offer himself as a candidate for the chair. He was promptly elected.

He now devoted himself to the task of designing and superintending the erection of the laboratory. His aim was to make it the best institution of its kind, with the latest apparatus and the most effective arrangements for research. He presented to the laboratory all the apparatus in his own possession and supplemented the Duke's gift by generous money contributions. With so many details to be taken care of, the structure and its appointments were not completed until 1874. The delay, while inevitable, was inconvenient. "I have no place," wrote Maxwell, "to erect my chair, but move about like the cuckoo, depositing my notions in the Chemical Lecture Room in the first term, in the Botannical in Lent and in the Comparative Anatomy in Easter." His "notions" were the courses he gave on heat, electricity and electromagnetism.

Maxwell's classic *Matter and Motion*, "a small book on a great subject," was published in 1876. About this time he contributed articles on various subjects —"Atom," "Aether," "Attraction," "Faraday," among others—to the famous ninth edition of the Encyclopaedia Britannica. His public lectures include a charming discourse "On the Telephone," which, though delivered when he was already very ill, is not only as clear as his best expositions but filled with gay, amusing asides. Speaking of "Professor Bell's invention," he commented on "the perfect symmetry of the whole apparatus—the wire in the middle, the two telephones at the ends of the wire, and the two gossips at the ends of the telephones. . . ." Maxwell spent five years editing 20 packets of unpublished scientific papers of Henry Cavendish. This splendid two-volume work, published in 1879, did much to fix the reputation of the immensely gifted 18th-century investigator, whose important work on electricity was unknown to his contemporaries because the results were confided only to his manuscripts. Maxwell repeated Cavendish's experiments and showed that he had anticipated major discoveries in electricity, including Ohm's law.

Glenlair

As Maxwell grew older, friends remarked on his "ever-increasing soberness" of spirit. He continued to see his

many friends, to write light verse and parodies, to promenade with his dog Toby, to play small practical jokes. But he became somewhat more reticent, and more and more concealed his feelings and reflections beneath an ironical shell. The tough, rational, Scotch commonsense cord of his nature had always been intertwined with threads of mysticism. He had faith in science; yet he was at bottom skeptical as to how much could be learned from science alone about nature and meaning. His contemporaries described him as both modest and intellectually scornful, tentative in his scientific opinions and dogmatic when others seemed to him to be immoderately self-assured.

The most striking of Maxwell's traits was his gentleness. An extraordinary selflessness characterized his relationship to those close to him. When his brother-in-law came to London to undergo an operation, Maxwell gave up the ground floor of his house to the patient and nurse and lived in a room so small that he frequently breakfasted on his knees because there was no room for a chair at the table. Mrs. Maxwell had a serious and prolonged illness in the last years of Maxwell's life, and he insisted on nursing her. On one occasion it is reported that he did not sleep in a bed for three weeks. But his work went on as usual and he was as cheerful as if he enjoyed the ordeal—which may indeed have been the case. Nor did he give the slightest sign of being downcast or show self-pity when his own fatal illness seized him.

In the spring of 1877 he began to be troubled with pain and a choking sensation on swallowing. For some strange reason he consulted no one about his symptoms for almost two years, though his condition grew steadily worse. His friends at Cambridge observed that he was failing, that the spring had gone out of his step. When he went home to Glenlair for the summer of 1879, he was so obviously weakening that he called for medical help. He was in terrible pain, "hardly able to lie still for a minute together, sleepless, and with no appetite for the food which he so required." He understood thoroughly that his case was hopeless, yet his main concern seemed to be about the health of his wife. On November 5 he died. "No man," wrote his physician, Dr. Paget, "ever met death more consciously or more calmly." When Maxwell was buried in Parton Churchyard at Glenlair, the world had not yet caught up with his ideas. Even today it has not fully explored the kingdom created by his imagination.

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